Extragalactic Gas at Low Redshift, April 2001, Pasadena
ASP Conference Series, Vol. TBD, 2001
Mulchaey, et al., editors

The Evolution of Neutral Gas in the Universe as Traced by Damped Lyman Alpha Systems

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Abstract.
We discuss our recent results on the statistical properties of damped Lyman alpha systems (DLAs) at low redshift ($z < 1.65$) (Rao & Turnshek 2000). Contrary to expectations, we found that the cosmological neutral gas mass density as traced by DLAs, Ω_{DLA}, does not evolve from redshifts $z \approx 4$ to $z \approx 0.5$ and that extrapolation to $z = 0$ results in a value that is a factor of ~ 6.5 times higher than what is derived from galaxies at the current epoch using HI 21 cm emission measurements. We review the current status of HI measurements at low redshift and at the current epoch, and discuss possible causes of this discrepancy.

1. Introduction

It was recognized in the mid-eighties that damped Lyman alpha systems (DLAs) reveal unique information about the evolutionary history of the Universe. Optical surveys of QSOs showed that DLAs trace the bulk of the observable neutral gas mass at high redshift, and therefore, that they can be used to study the formation and evolution of galaxies. A particularly compelling result was that the comoving neutral gas mass density in DLAs at redshift $z \approx 3.5$ was comparable to the luminous mass density observed in galaxies at the current epoch. There also seemed to be evidence for a decline in the neutral gas mass density from $z \approx 3.5$ to $z \approx 1.7$ that extrapolated to the value inferred from gas-rich galaxies at $z = 0$ (Wolfe et al. 1986; Turnshek et al. 1989; Lanzetta et al. 1991; Rao & Briggs 1993). This was interpreted as evidence for gas depletion due to star formation, and DLAs were thought to trace the evolution of the progenitors of present-day disk galaxies.

However, several studies carried out during the second half of the last decade have shown that the interpretation is not so straightforward. Groundbased surveys can search for DLA lines only beyond $z = 1.65$ when the Lyα line moves into the optical region of the electromagnetic spectrum. Thus, until the recent IUE and HST surveys for DLAs (Lanzetta, Wolfe, & Turnshek 1995; Rao, Turnshek, & Briggs 1995; Jannuzi et al. 1998; Rao & Turnshek 2000, henceforth, RT2000), about 70% of the Lyα Universe was unexplored. The RT2000 survey, which we discuss in this contribution, more than doubled the number of known low-redshift DLAs. We used a bootstrapping method which relied on the statistics of MgII absorption lines to identify DLAs. The results,

although still limited by small number statistics, show that Ω_{DLA} is consistent with remaining constant from redshifts $z \approx 4$ to $z \approx 0.5$ and that extrapolation to $z = 0$ results in a value that is a factor of ~ 6.5 times higher than what is derived from galaxies at the current epoch. The DLA redshift number density is only marginally consistent with evolution between redshifts $z \approx 4$ and $z \approx 0.5$. This implies that DLAs may be a slowly evolving population that do not undergo significant gas depletion and, by extension, star formation.

Apart from the low-redshift DLA statistics, results from metallicity studies, kinematics, and direct imaging of the DLAs have shown that the "DLA - disk galaxy" paradigm is inadequate. Pettini and collaborators (e.g. Pettini et al. 1997, Pettini et al. 1999, Pettini et al. 2000) have shown that there is no obvious tendency for DLA metallicities to increase with decreasing redshift and approach the solar value. However, there is considerable scatter in the individual metallicities which is most likely caused by the wide range of formation histories and galaxy types responsible for the DLAs. In fact, Pettini et al. (1999) have also concluded that the known DLAs are unlikely to trace the galaxy population responsible for the bulk of the star formation.

Prochaska & Wolfe (1997; 1998) have used high-resolution spectra of the metal-line profiles associated with DLAs to argue that the kinematic profiles of the DLA absorbing regions are more consistent with models of rotating HI disks than any other single type of model. The kinematics have also been shown to be consistent with gas in-fall due to merging (Haehnelt, Steinmetz, & Rauch 1998), randomly moving clouds in a spherical halo (McDonald & Miralda-Escudé 1999), and multiple gas disks in a common halo (Maller et al. 2000). Therefore, it seems most likely that, consistent with other current findings, the kinematics of DLA absorbing regions arise from a mix of kinematic structures, including some rotating gaseous disks.

There is now direct evidence from imaging studies that the morphological types of DLA galaxies are indeed mixed. See Rao & Turnshek (1998), Turnshek et al. (2001), and Nestor et al. (2001, these proceedings) for ground-based imaging results on some of our low-redshift DLA fields. HST images of other low-redshift DLA absorbers have also revealed a mixed population (Le Brun et al. 1997; Bouché et al. 2001). Turnshek, Rao, & Nestor (2001, these proceedings) compare the properties of low-redshift DLA galaxies to the properties of gas-rich galaxies at $z = 0$.

Thus, there has been a shift in our interpretation of the nature of the DLA galaxy population, consistent with the idea that DLAs arise in giant hydrogen clouds that could be associated with any type of galaxy or protogalaxy (Khersonsky & Turnshek 1996). Here, we elaborate on some of the statistical results from our DLA survey.

2. The Low-Redshift DLA Survey

We recently completed an efficient non-traditional (but unbiased) HST survey to discover DLAs at redshifts $z < 1.65$ (RT2000). Our survey relied on observations of Lyα absorption in identified MgII systems (which can be identified from the ground for $z > 0.1$), where the incidence of MgII is known as a function of the MgIIλ2796 rest equivalent width, $W_0^{\lambda 2796}$ (e.g. Steidel & Sargent 1992). The

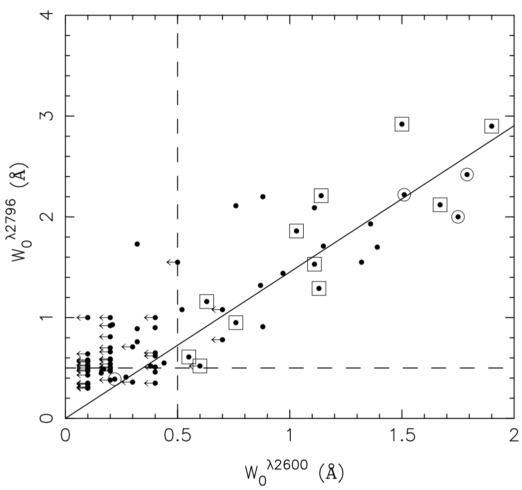

Figure 1. A plot of MgII $W_0^{\lambda 2796}$ versus FeII $W_0^{\lambda 2600}$. The DLAs from the RT2000 sample are marked with open squares. The open circles represent previously known 21 cm absorbers that were excluded from our unbiased MgII sample. Left pointing arrows indicate upper limits to the measured value of $W_0^{\lambda 2600}$. The horizontal and vertical dashed lines identify the region for which $W_0^{\lambda 2796} > 0.5$ Å and $W_0^{\lambda 2600} > 0.5$ Å; half of these are DLAs.

empirical fact that all DLA absorbers have MgII absorption (Turnshek et al. 1989; Lu et al. 1993; Wolfe et al. 1993; Lu & Wolfe 1994) greatly improves the efficiency of searches for DLA at low redshift. With our survey technique, we uncovered 12 DLA lines in 87 MgII systems with $W_0^{\lambda 2796} \geq 0.3$ Å (a success rate of ≈14%). Two more DLAs were discovered serendipitously. In total our survey increased the number of known low-redshift DLA absorbers more than two-fold (previously known low-redshift DLAs were mostly identified via 21 cm absorption).

2.1. The Statistical Properties of Low-Redshift DLAs

Since we observed the fraction of MgII systems with DLA, we determined the incidence of DLAs at low redshift by bootstrapping from the MgII statistics. By fitting Voigt damping profiles to the Lyα lines in our UV spectra, we deduced N_{HI} for each DLA system and determined the low-redshift cosmological neutral gas mass density of DLA absorbers. Specifically, our survey results indicate:

(1) Approximately 50% of the systems with $W_0^{\lambda 2796} \geq 0.5$ Å *and* FeII $W_0^{\lambda 2600} \geq 0.5$ Å have DLA absorption (Figure 1). Thus, we uncovered a new selection criterion for the identification of DLAs. Moreover, all the non-DLAs in this regime have HI column densities $N_{HI} \geq 10^{19}$ atoms cm^{-2}. We also found that with the exception of the known $z = 0.692$ 21 cm absorber towards 3C 286 which has unusually low metal-line equivalent widths ($W_0^{\lambda 2796} = 0.39$ Å and $W_0^{\lambda 2600} = 0.22$ Å, Cohen et al. 1994), all of the DLAs lie in the upper-right region of the plot where $W_0^{\lambda 2796} > 0.5$ Å and $W_0^{\lambda 2600} > 0.5$ Å.

(2) The incidence of DLAs per unit redshift, n_{DLA}, is observed to decrease with decreasing redshift (Figure 2). The observed trend in n_{DLA} implies significant evolution only if the $z = 0$ data point, which is derived from 21 cm

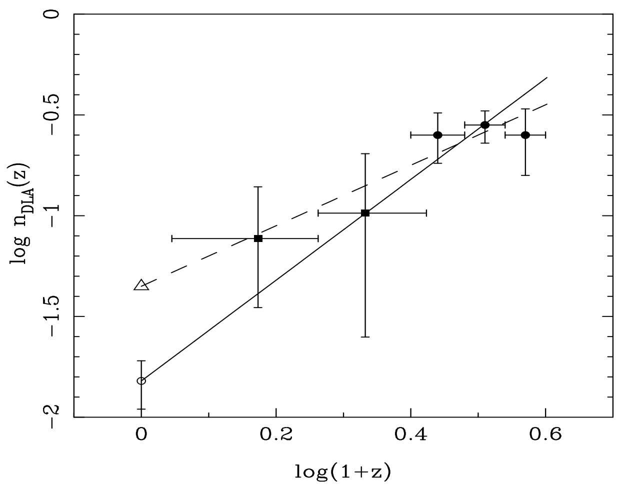

Figure 2. The number density redshift distribution of DLAs. Our low-redshift results are shown as solid squares (RT2000). A Malmquist bias correction factor has been applied to the high-redshift data of Wolfe et al. (1995) and the results are shown as solid circles. See RT2000 for details. The open circle is derived from the observed HI distribution in local spiral galaxies (Rao & Briggs 1993). The solid line has $\gamma = 2.5$ and is forced to pass through the $z = 0$ data point, the dashed line has $\gamma = 1.5$ and does not include the $z = 0$ data point. Extrapolation of this power-law to $z = 0$ (the open triangle) results in a value that is ~ 3 times larger than the observed incidence at $z = 0$.

observations of gas-rich spirals (Rao & Briggs 1993), is included in the analysis. Two power laws of the form $n_{DLA}(z) = n_0(1+z)^\gamma$ are shown. For $\Lambda = 0$ cosmologies, n_{DLA} is consistent with no intrinsic evolution if $\gamma = 1.0$ for $q_0 = 0$ or if $\gamma = 0.5$ for $q_0 = 0.5$. The solid line in Figure 2, which goes through the $z = 0$ data point, has exponent $\gamma = 2.5$ and indicates significant evolution. The dashed line, which excludes the $z = 0$ data point, has $\gamma = 1.5$ and is only marginally consistent with evolution. Extrapolation to $z = 0$ (the open triangle) results in a value that is ~ 3 times larger than the observed incidence at $z = 0$.

(3) The cosmological mass density of neutral gas in low-redshift DLA absorbers, Ω_{DLA}, is found to be comparable to that observed at high redshift (Figure 3). The error bars are large because $\Omega_{DLA}(z)$ is very sensitive to the small number of systems which have the highest column densities. For $q_0 = 0.5$, $\Omega_{DLA}(z)$ is a factor of ~ 6.5 times larger than the value for $\Omega_{gas}(z = 0)$ inferred from local 21 cm observations.

(4) The HI column density distribution (CDD) of the low-redshift DLA absorber population is very different in comparison to high-redshift DLA absorbers, and in comparison to the column density distribution inferred from local spirals (Figure 4). The low-redshift DLAs exhibit a significantly larger fraction of very high column density systems in comparison to determinations at both high redshift and locally. At no redshift does the CDD fall-off in proportion to $\sim N_{HI}^{-3}$. An $\sim N_{HI}^{-3}$ fall-off is theoretically predicted for disk-like systems (e.g. Milgrom 1988) and this is, in fact, observed locally in spiral samples (Rao & Briggs 1993; Zwaan et al. 1999).

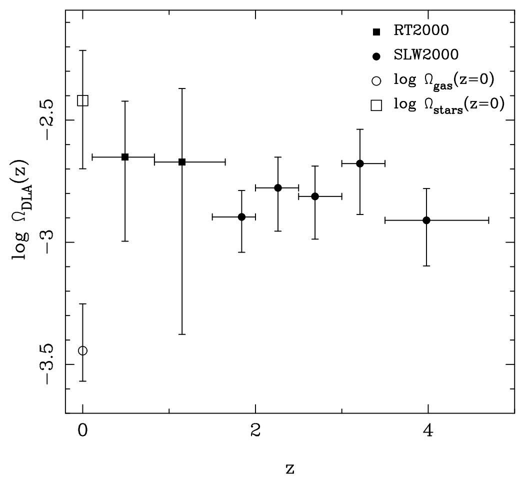

Figure 3. The cosmological mass density of neutral gas as a function of redshift for $H_0 = 65$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$, and $\Lambda = 0$. The data points for $z > 1.5$ are from Storrie-Lombardi and Wolfe (2000). The open circle at $z = 0$ is the local neutral gas mass density as measured by Rao & Briggs (1993) and the open square at $z = 0$ is the local luminous mass density in stars (Fukugita, Hogan, & Peebles 1998).

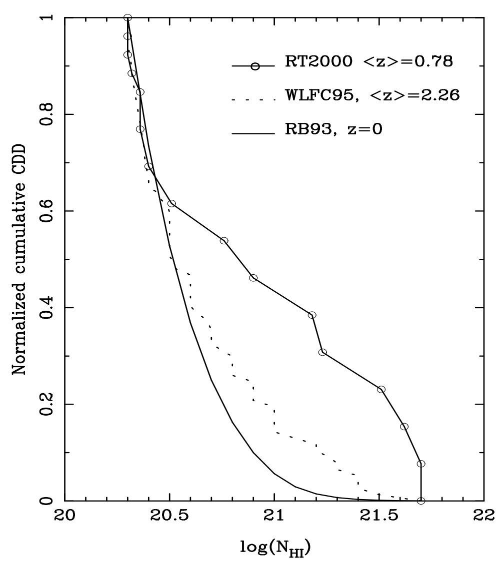

Figure 4. The normalized cumulative column density distributions for the low-redshift DLA sample (RT2000), the high-redshift DLA sample (Wolfe et al. 1995), and local galaxies (Rao & Briggs 1993).

Despite the increase in the number of known low-redshift DLAs, the statistics are still dominated by small numbers leading to large error bars on n_{DLA} and Ω_{DLA}. It could be argued that these quantities are also consistent with a real decrease between $z \approx 4$ and $z \approx 0.5$. However, the CDD at low redshift is very significantly different from that at high redshift. There is only a 2.8% probability that the two samples are drawn from the same parent population. Also, the low-redshift DLA sample is different from the local spiral galaxy population at the 99.99% confidence level.

3. Discussion

In summary, the observational results on DLAs over the past decade have shown that their redshift number density, cosmological mass density, and metallicities show little evolution from redshifts $z \approx 4$ to $z \approx 0.5$. We have also seen that DLA galaxies cover a wide range of gas-rich morphological types from predominantly dwarf and low surface brightness galaxies to some spirals.

That they are a slowly evolving population implies that either: (1) they do not trace the bulk of the galaxy population responsible for star formation, i.e., they are a different population than the galaxies that are used to determine the star formation history of the Universe, or (2) that the galaxy population responsible for star formation is a small subset of the DLA galaxy population. If the first possibility holds, this is probably the result of a selection effect in that optical surveys of QSOs preferentially probe lines of sight that are relatively dust free. These sight lines must avoid star forming regions that are enshrouded in metal-enriched dust (Pei, Fall, & Hauser 1999). Indeed, the models of Pei, Fall, & Hauser (1999) imply that as much as ∼70% of the neutral gas mass is being missed by DLA surveys. However, the recent study of DLAs detected in a sample of radio-selected quasar spectra by Ellison et al. (2001) suggests that the effect might be less important.

Our results on the incidence of DLAs show that n_{DLA} is only marginally consistent with evolution from $z \approx 4$ to $z \approx 0.5$, and that the extrapolated value of $n_{DLA}(z)$ at $z = 0$ is higher than that deduced from 21 cm emission data of nearby galaxies by a factor of ~ 3 (see Figure 2). We also found that Ω_{DLA} does not evolve from $z \approx 4$ to $z \approx 0.5$ and that the extrapolated value at $z = 0$ is a factor of ∼6.5 times higher than the neutral gas mass density deduced from gas-rich galaxies at the present epoch (Figure 3). Thus, the QSO absorption-line results are highly inconsistent with the results from 21 cm observations of local galaxies. Recently, Churchill (2001) used HST archival spectra to determine the incidence of MgII systems at $z \approx 0.05$ and, based on the RT2000 method of bootstrapping from MgII statistics and the assumption of no evolution in the MgII-to-DLA statistics, derived a value for $n_{DLA}(z \approx 0.05)$ which is essentially equivalent to the RT2000 value for $n_{DLA}(z \approx 0.5)$. He further noted that if the CDD of DLAs did not evolve from $z \approx 0.5$ to $z \approx 0.05$, then $\Omega_{DLA}(z \approx 0.05)$ would also be consistent with the RT2000 result for $\Omega_{DLA}(z \approx 0.5)$. The implication, then, would be that Ω_{DLA} is constant from $z \approx 4$ to nearly the current epoch, i.e., $z \approx 0.05$. If the Churchill (2001) results are confirmed with follow-up observations of the corresponding Lyα lines then the discrepancy

between the QSO absorption line results and 21 cm emission measurements of local galaxies would have to be explained.

3.1. At low redshift

It is possible that we are so dominated by errors from the statistics of small numbers, that our sample just happened to have a higher fraction of the highest column density systems by sheer chance. As mentioned above, the Churchill (2001) result on $\Omega_{DLA}(z = 0.05)$ was derived assuming that the CDD of DLAs did not evolve from $z \approx 0.5$ to $z = 0.05$. So that result is also subject to question in the same way. The only way around this is to conduct larger surveys for DLAs at low redshift. In addition to improving the statistical uncertainties, this would permit a better determination of the shape of the HI CDD at large column densities, effectively allowing a determination of the maximum HI column density. Understanding this turn-down in column density is important for the determination of Ω_{DLA}. It is also worth reiterating that the redshift interval $0 < z < 1.65$ includes the most recent $\sim$70% of the age of the Universe. We certainly require more than a dozen or so DLAs to do justice to this era.

It might be argued that our technique of selecting from a MgII sample biases the DLA sample towards higher column densities. However, we have shown that our data are not consistent with this (see RT2000). There is no trend between MgII $W_0^{\lambda 2796}$ and HI column density. While we used a $W_0^{\lambda 2796}$ detection threshold of 0.3Å, all but one of our DLAs have $W_0^{\lambda 2796} > 0.6$Å (the one system has $W_0^{\lambda 2796} = 0.52$Å). Thus, we believe that our empirically-determined cut-off in $W_0^{\lambda 2796}$ is sound. It was also suggested by Frank Briggs at this conference that a higher $W_0^{\lambda 2796}$ cut-off should be used to search for DLAs since they are probably more indicative of the presence of a DLA system. Moreover, the Steidel & Sargent (1992) MgII study showed that systems with $W_0^{\lambda 2796} > 1.0$ Å evolved away faster than those with $W_0^{\lambda 2796} > 0.6$Å. This might, he argued, result in a smaller value for $\Omega_{DLA}(z \approx 0.5)$. We find that the results on $\Omega_{DLA}(z \approx 0.5)$ from the two $W_0^{\lambda 2796}$ threshold samples in our data set are consistent with each other; of course, the error bars for the $W_0^{\lambda 2796} > 1.0$Å sample are even larger.

It is also a concern that our QSO samples might be influenced by gravitational lensing bias; DLA galaxies magnify QSOs, preferentially introducing them into optically selected samples. Le Brun et al. (2000) have shown this effect to be less than 0.3 magnitudes for their sample of 7 DLA galaxies. They also point out that our QSO sample is brighter than theirs and that magnification bias may, therefore, be more important for our sample. The QSOs with the highest column density DLAs in our sample have not been imaged with HST, and so the possibility of lensing by the DLA galaxies has not been studied with the greatest possible sensitivity. On the other hand, our ground-based studies suggest that DLA galaxies are not highly luminous, and therefore, massive galaxies.

In any case, it is clear that in addition to increasing DLA sample sizes, biases due to MgII selection, dust obscuration, and the effect of gravitational lensing could be assessed more carefully.

3.2. At the present epoch

We should also re-examine the $z = 0$ statistics. In Rao & Briggs (1993) we used the best available optical luminosity functions known at that time in conjunction with empirical HI mass – optical luminosity relations of gas-rich galaxies to calculate the HI mass density locally. This is the value plotted in Figure 3. The upper error bar has been modified slightly as explained in Rao, Turnshek, & Briggs (1995). Fall & Pei (1993) derived approximately the same value using mean values of the local luminosity density and M_{HI}/L_B. This exercise was repeated by Natarajan & Pettini (1997) using more recent optical luminosity functions and they confirmed the Rao & Briggs (1993) result. For comparison, the results on $\Omega_{gas}(z = 0)$ were $2.4\times10^{-4}h^{-1}$ (Rao & Briggs 1993), $2.6\times10^{-4}h^{-1}$ (Fall & Pei 1993), and $2.5 \times 10^{-4}h^{-1}$ (Natarajan & Pettini 1997).

Direct measurements of the local gas mass density using HI 21 cm emission surveys have also been found to be consistent with the above results. The Arecibo HI Strip Survey (AHISS, Zwaan et al. 1997) performed the most sensitive search for local 21 cm emission to date, being 5 times more sensitive than the Arecibo Dual Beam Survey (ADBS) of Rosenberg & Schneider (2000), although the latter covered a larger volume. The limiting column density of the Zwaan et al. survey was 10^{18} cm^{-2} at the 5σ level for gas filling the telescope beam, and they had the capability of detecting HI masses of $6 \times 10^5h^{-2}\mathrm{M}_\odot$ at $7h^{-1}$ Mpc. For comparison, HIPASS, which is a blind 21 cm survey of the southern sky, reached a limiting column density of 7×10^{17} cm^{-2} at the 3σ level and a mass limit of $\sim 7 \times 10^7h^{-2}$ M$_\odot$ at $7h^{-1}$ Mpc (Kilborn, Webster, & Staveley-Smith 1999; Kilborn 2001). All three 21 cm surveys have been used to construct the local HI mass function. The faint end slope of the HI mass function has been the focus of much debate since it bears directly on the values of $\Omega_{gas}(z = 0)$ and $n(z = 0)$ (Figures 2 and 3). Moreover, a large faint end slope might imply the existence of a new dwarf galaxy population that has not been identified optically. For comparison, Zwaan et al. (1997) derive a slope of $\alpha = 1.2$, Rosenberg & Schneider (2001, these proceedings) get $\alpha = 1.5$, while Kilborn (2001) derives $\alpha = 1.52$ (where α is the standard Schechter luminosity function parameter). The integral of the HI mass function is an estimate of the total HI mass density at $z = 0$, and its ratio with the critical mass density at the current epoch gives $\Omega_{HI}(z = 0)$. A correction for a neutral gas composition of 75% H and 25% He by mass then gives $\Omega_{gas}(z = 0)$. The results on $\Omega_{gas}(z = 0)$ for the three surveys are $2.7 \times 10^{-4}h^{-1}$ (Zwaan et al. 1997), $3.8 \times 10^{-4}h^{-1}$ (Kilborn 2001), and $4.4 \times 10^{-4}h^{-1}$ (from data in Rosenberg & Schneider 2001, these proceedings).

Thus, the value of $\Omega_{gas}(z = 0)$ derived from optical luminosity functions is consistent with the value derived from HI mass functions. As expected, the HI mass functions with $\alpha \sim 1.5$ result in slightly larger values for $\Omega_{gas}(z = 0)$, but only at the $\sim 2\sigma$ level. The similarity between the HI mass function estimated from AHISS with that derived from optical luminosity functions (Briggs & Rao 1993) led Zwaan et al. (1997) to conclude that there is no large population of HI-rich galaxies (e.g. low surface brightness or dwarf) that have been missed by optical galaxy surveys. See also Zwaan, Briggs, & Sprayberry (2001) who show that the optical luminosity function of HI selected galaxies is in agreement with the luminosity function of optically selected late-type galaxies. However, based on the sensitivities of the three 21 cm surveys discussed above, the possibility of

there being objects with masses lower than $\sim 10^7$ M$_\odot$ that contain DLA column densities, but that have a mean column density less than $\sim 10^{18}$ cm^{-2} within the telescope beam cannot be ruled out.

Rosenberg & Schneider (2001, these proceedings) have also suggested that the faint-end slope of the ADBS HI mass function, $\alpha = 1.52$, is large enough to make the contribution of low-HI-mass galaxies important to the DLA cross-section at $z = 0$. They derive a value for $n(z = 0)$ that is a factor of ~ 5.5 higher than our estimate from a complete sample of 27 gas-rich galaxies (see Rao, Turnshek, & Briggs 1995 and Turnshek, Rao, & Nestor 2001, these proceedings). While the ADBS sample covers a larger range in HI masses (5×10^7M$_\odot$ to 2×10^{10}M$_\odot$) compared to our sample (5×10^8M$_\odot$ to 2×10^{10}M$_\odot$), the cross-sectional areas of our galaxies at the 2×10^{20} atoms cm^{-2} HI column density contour are systematically lower by a factor of ~ 4. This might possibly account for the larger value of $n(z = 0)$ that they derive from their data set.

4. Concluding Remarks

Observations over the past several years have led us to a new paradigm for DLAs, namely, that DLAs trace clouds of neutral gas whose properties have not changed significantly between $z \approx 4$ and $z \approx 0.5$, and that these clouds arise in a variety of gas-rich galaxy types. There exists a discrepancy of about a factor of 6.5 between the cosmological neutral gas mass density at $z = 0$ as inferred from DLA statistics and 21 cm emission measurements of local galaxies. Whether this discrepancy is due to small-number statistics of DLAs at low redshift, a real selection difference, or real evolution can only be resolved with more and better data at low redshift and at $z = 0$.

This research has been supported by STScI grant GO-06577.01-95A and NASA LTSA grant NAG5-7930.

References

Bouché, N., et al. 2001, ApJ, 550, 585

Briggs, F., & Rao, S. 1993, ApJ, 417, 494

Churchill, C. W. 2001, ApJ, in press (astro-ph/0105044)

Cohen, R. D., et al. 1994, ApJ, 421, 453

Ellison, S. L., Yan, L., Hook, I. M., Pettini, M., Wall, J. V., & Shaver, P. 2001, astro-ph/0107347

Fall, S. M., & Pei, Y. C. 1993, ApJ, 402, 479

Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

Haehnelt, M., Steinmetz, M., & Rauch, M. 1998, ApJ, 495, 64

Jannuzi, B. et al. 1998, ApJS, 118, 1

Kilborn, V., Webster, R. L., & Staveley-Smith, L. 1999, PASA, 16, 8

Kilborn, V. A. 2001, Ph.D. Thesis, University of Melbourne

Khersonsky, V. K., & Turnshek, D. A. 1996, ApJ, 471, 657

Lanzetta, K. M., et al. 1991, ApJS, 71, 1

Lanzetta, K. M., Wolfe, A. M., & Turnshek, D. A. 1995, ApJ, 440, 435

Le Brun, V., Bergeron, J., Boissé, & Deharveng, J. M. 1997, A&A, 321, 733

Le Brun, V., Smette, A., Surdej, J., & Claeskens, J.-F. 2000, A&A, 363, 837

Lu, L., Wolfe, A. M., Turnshek, D. A., & Lanzetta, K. M. 1993, ApJS, 84, 1

Lu, L., & Wolfe. A. M. 1994, AJ, 108, 44

Maller, A. H., Prochaska, J. X., Somerville, R. S., & Primack, J. R. 2000, astro-ph/0002449

McDonald, P., & Miralda-Escudé, J. 1999, ApJ, 519, 486

Milgrom, M. 1988, A&A, 202, L9

Natarajan, P., & Pettini, M. 1997, MNRAS, 291, L28

Nestor, D., Rao, S., Turnshek, D. A., Monier, E., Lane, W., and Bergeron, J. 2001, these proceedings

Pei, Y. C., Fall, S. M., & Hauser, M. G. 1999, ApJ, 522, 604

Pettini, M., Smith, L. J., King, D. L., & Hunstead, R. W. 1997, ApJ, 486, 665

Pettini, M., Ellison, S., Steidel, C., & Bowen, D. 1999, ApJ, 510, 576

Pettini, M., et al. 2000, ApJ, 532, 65

Prochaska, J. X., & Wolfe, A. M. 1997, ApJ, 487, 73

Prochaska, J. X., & Wolfe, A. M. 1998, ApJ, 507, 113

Rao, S. M., & Briggs , F. H. 1993, ApJ, 419, 515

Rao, S. M., Turnshek, D. A., & Briggs, F. H. 1995, ApJ, 449, 488

Rao, S. M., & Turnshek, D. A. 1998, ApJ, 500, L115

Rao, S. M., & Turnshek, D. A. 2000, ApJS, 130, 1

Rosenberg, J. L., & Schneider, S. E. 2000, ApJS, 130, 177

Rosenberg, J. L., & Schneider, S. E. 2001, these proceedings

Smette, A., Claeskens, J.-F., & Surdej, J. 1997, New Astronomy, 2, 53

Steidel, C. C., & Sargent, W. L. W. 1992, ApJS, 80, 1

Turnshek, D. A., et al. 1989, ApJ, 344, 567

Turnshek, D. A., Rao, S., Nestor, D., Lane, W., Monier, E., Bergeron, J., & Smette, A. 2001, ApJ, 553, 288

Turnshek, D. A., Rao, S., & Nestor, D. 2001, these proceedings

Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249

Wolfe, A. M., Turnshek, D. A., Lanzetta, K. M., & Lu, L. 1993, ApJ, 404, 480

Wolfe, A. M., Lanzetta, K. M., Foltz, C. B., & Chaffee, F. H. 1995, ApJ, 454, 698

Zwaan, M. A., Briggs, F. H., Sprayberry, D., & Sorar, E. 1997, APJ, 490, 173

Zwaan, M. A., Verheijen, M. A. W., & Briggs, F. H. 1999, PASA, 16, 100

Zwaan, M. A., Briggs, F. H., & Sprayberry, D. 2001, MNRAS, in press (astro-ph/0107448)